RECENT OBSERVATIONS ON THE DYNAMICS OF THE PULMONARY CIRCULATION*

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The essential function performed by the pulmonary circulation is to transfer blood from the right to the left ventricle and thereby to bring it into intimate contact with alveolar air. Still another function has been assigned to the lesser circuit, namely the storage of blood in the pulmonary vessels. Blood stored in the lungs could be used as an emergency reserve to help fill the left ventricle when sudden increased demand in systemic blood flow is not paralleled by an increased venous return to the right heart and would, if need be, damp the effect of unequal discharge of both ventricles.

For many decades physiologists have tried to decide whether blood flow, pressures and volume variations in the pulmonary circulation are the expression of the passive position taken by this circuit in the general phenomena of the vascular system or whether they are affected by changes in pulmonary vascular resistance regulated by an active vasomotor system. I shall attempt in this presentation to discuss, in a limited way, our present day knowledge of this problem in the light of recent physiologic and physiopathologic evidence.

The two chief characteristics of the dynamics of the pulmonary circulation may best be stated as follows: (a) the blood flow through the lungs is identical to the blood flow through the entire systemic circulation, except for momentary differences, (b) the pressures in the right ventricle, pulmonary artery and capillaries are lower than in corresponding structures of the systemic circulation.

From these characteristics several facts may be deduced. First: the energy developed by the right ventricle in performing its mechanical work, i.e., stroke volume times mean pressure in the pulmonary artery,

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is much less than that developed by the left ventricle. This explains the unequal muscular development of both ventricles.

Second: the small rise in pressure in the pulmonary artery during ejection is due to its greater distensibility in proportion to its capacity as compared to the aorta. Pressure-volume diagrams obtained with sections of both large vessels bear out this fact directly,[1] while measurement of pulse wave velocity[2] (3 meters per second in the pulmonary artery of the dog as compared to 4-5 meters in the aorta) confirms it indirectly.

Third: the resistance to flow in the pulmonary vessels is much less than in the systemic vessels, the mean pressure difference between the pulmonary artery and the left auricle being 1/5 of the mean pressure difference between the aorta and the right auricle. This low resistance is chiefly related to particular details of structures of the vessels: (a) the arterioles are few and their walls show very little smooth muscle, (b) the precapillaries are numerous and very large, sometimes larger than the arterioles, (c) the capillaries are short, with remarkable ability to increase their capacity by simple distention, (d) the veins are short and very distensible.

Fourth: the pulmonary circulation time must be short and the time of exposure of blood to alveolar air, likewise very short.

Blood pressures, blood volume, and circulation time in the pulmonary circulation of dog and normal man. One of the chief obstacles to accurate measurements of pressures in various parts of the pulmonary circulation of dogs lies in the difficulty of access to these parts and the abnormal physiologic conditions under which measurements have usually been obtained. Very recently, Hamilton, Woodbury and Vogt[3] have developed a method which permits the recording of pressures in the pulmonary artery and vein of unanesthetized, intact dogs, several weeks or months after their recovery from an operation during which the distal ends of special cannulae were placed in contact wtih the pulmonary vessels, while their proximal ends were sewn under the skin of the thoracic cage; these cannulae served later as a guide for the introduction into the vessels of needles connected to manometers. By this method pressures in the pulmonary artery of several dogs averaged 37/10 mm. Hg. with a mean pressure of 20 mm. Hg., while the average pulmonary vein pressure varied during one cardiac cycle between 12 and 2 mm. Hg. The pressure gradient between artery and vein, largest during early systole, reached practically zero at the end of diastole,

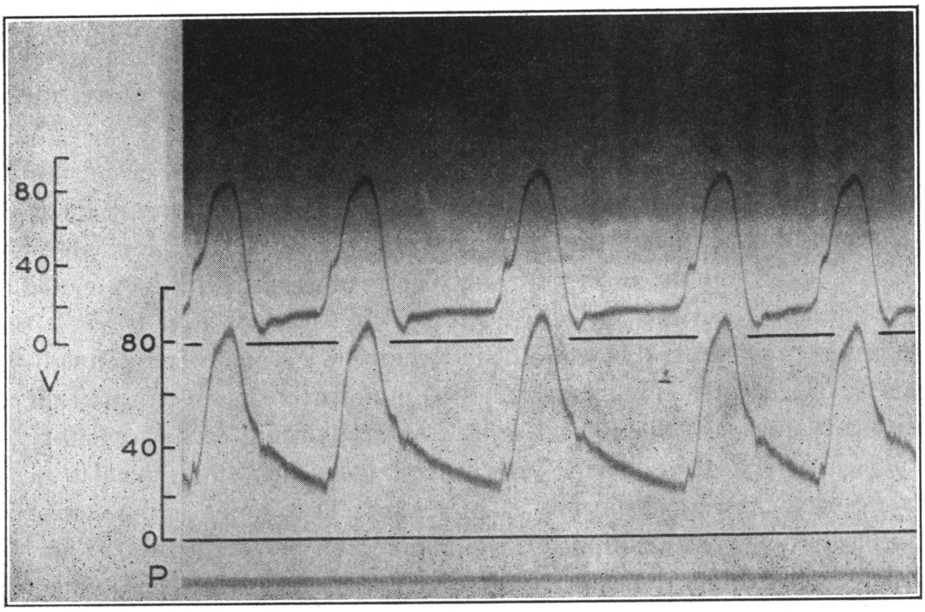

Fig. 1. Simultaneous blood pressure tracings in the right ventricle (top) and the pulmonary artery (bottom). *In this and the following records scales are in mm Hg. (For description of this and of the following figures see text.)*

another evidence of the small resistance to flow in the intervening arterioles and capillaries. In the course of many experiments they observed that pressure in the pulmonary artery rose with larger output from the right ventricle, while pressures in the pulmonary veins increased with some lag; but that a rise in pulmonary vein pressure closely followed increased resistance in the systemic circulation.

With Bloomfield, Lauson, Breed, and Richards[4] we have measured pressures in the right ventricle in 14 normal human subjects under metabolic conditions which were nearly basal, the blood flow in this group averaging 3.6 liters/min/m^2B.S. as compared to a standard figure of 3.1 liters. The ventricular systolic pressure averaged 25 mm. Hg. ranging from 18 to 30 mm. Hg., the pulse pressure, i.e., the difference between diastolic-filling pressure and peak of systolic pressure, ranged within the narrow limits of 21 to 27 mm. Hg.

Satisfactory records of pulmonary arterial pressures in man have, up to now, been difficult to obtain, on account of very marked superimposed oscillations due to motions of the catheter. In 4 normal individuals, where satisfactory tracings were recorded, the pressures averaged 25/8 mm. Hg. with a mean pressure of 15 mm. Hg. Fig. 1

illustrates an excellent record of simultaneous pressure tracings, in the right ventricle and pulmonary artery, obtained through a double lumen catheter in a patient in congestive heart failure where, therefore, the systolic and diastolic pressures were high.[5]

With a large blood flow and a low resistance, the mean circulation time is necessarily very rapid. After allowance is made with most methods used in experimental and clinical work, for transit of the chemical substance through the extra-pulmonary parts of its circuit, it is estimated that blood reaches the capillaries within 2 to 3 seconds after it has left the right ventricle, and reaches the left ventricle 2 seconds later. Roughton,[6] very recently, using a new method in normal man, investigated the capillary time, i.e., the average length of time during each circulatory cycle in which gas exchange between capillary blood and alveolar air takes place. It is, approximately, ¾ of a second at rest and ⅓ of a second during heavy work. Within this short interval a perfect or nearly perfect gaseous equilibrium, as is well established now, is reached, which speaks in favor of the high degree of efficiency attained by the pulmonary circulation in performing its essential respiratory function. Making apparently sound assumptions, Roughton went on to calculate the total area of the capillary walls and the total volume of capillary blood involved in this exchange—respectively 38 square meters and 60 cc. during rest. On the basis of the probably correct assumption that the capillary blood volume in the pulmonary vascular system constitutes, as in other regional vascular systems about 15 per cent of the entire volume, the circulating pulmonary blood volume under basal conditions would amount to 400 cc. or 8 per cent of the total circulating blood volume. This figure compares well with the value of approximately 10 per cent given by Kuno[7] who measured pulmonary blood volume directly on dogs in the heart-lung preparation.

A summary of standard measurements of blood flow, pressures, pulmonary blood volume in normal man under basal condition is given in Table I. Circulating pulmonary blood volume, and pressure, in the lesser circulation, are, however, not static as would appear from this Table. They are continuously influenced by the output of the right ventricle, the resistance in the pulmonary circuit and the effect of back pressures in the pulmonary veins resulting from variations in left ventricular output. We shall, therefore, consider the dynamic relationship between flow, pressure, and circulating blood volume in the lesser circulation

TABLE I

SOME MEASUREMENTS OF THE PULMONARY CIRCULATION IN NORMAL MAN, SUPINE AND UNDER BASAL CONDITION

Blood Flow	lit/min	5.5
	lit/min/m² BS	3.1
Pressures		
Right Ventricle		
Syst/Diast	mm Hg	25/2
Pulmonary Artery		
Syst/Diast	mm Hg	25/8
Mean	mm Hg	15
Capillary		
Mean	mm Hg	between 8—2 (appx.)
(Oncotic)	mm Hg	25
Blood Volume as a fraction of Total Blood Volume		1/10

under varying physiological conditions, such as changes in position and in intrathoracic pressure.

Increase and decrease in pulmonary blood volume, according to the experimental work of Drinker, Churchill and Ferry[8] are easily accommodated by the capacious vascular bed. The blood volume increases with larger discharge of the right ventricle and smaller discharges of the left and conversely decreases with smaller discharges of the right ventricle and larger of the left. Variations in the circulating blood volume within the lungs necessarily originate during the short periods in which, under normal physiological conditions, the two ventricular outputs differ. There is good evidence also brought out by the work of Hamilton and his co-workers,[9] using the dye technique, that under physiologic conditions in man, pulmonary blood volume variations are positively correlated with stroke volume variations.

Measurement of the vital capacity, within the limits of accuracy of this procedure, is also an excellent means of demonstrating qualitative changes in pulmonary blood volumes, since Drinker, Peabody and Blumgart[10] have shown that storage of blood in the lungs is at the expense of the air spaces. It is well known that vital capacity decreases in normal man as he moves from the standing or sitting to the recumbent position. In the latter position venous return from the abdomen and lower limbs

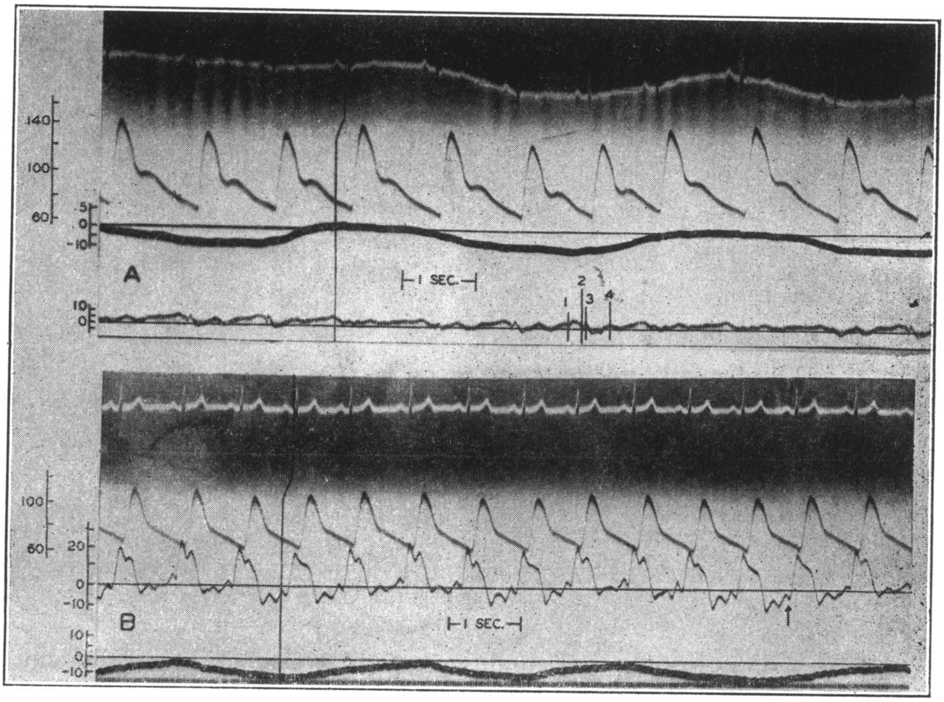

Fig. 2. Simultaneous blood pressure tracings in (a) femoral artery, pleura, and right auricle and in (b) femoral artery, right ventricle and pleura. Simultaneous electrocardiographic tracings at top of each record—vertical line indicates parallax between electrocardiogram and blood pressure tracings.

to the thorax is increased, the stroke volume of the right ventricle becomes larger, causing a rise in the pulmonary artery mean pressure and active congestion of the lungs. A convincing demonstration of the increase of the cardiac output in the recumbent position has been given by McMichael and Sharpey-Schafer[11] using the "Direct Fick" method. The importance of the increase of the venous return in the mechanism under discussion is stressed by the observations made in man by Hamilton and Morgan[12] and later by Dow,[13] which indicated that the decrease in vital capacity associated with a change to the recumbent position is lessened or prevented by the application of pressure cuffs on the four limbs.

Influence of various types of breathing upon blood pressure and blood flow in the pulmonary circulation. In the course of still unpublished studies of the effects of intrathoracic pressure variations upon the dynamics of the pulmonary circulation in man done in collaboration with Lauson, Bloomfield, Breed and Richards,[14] and more recently with Motley, we have taken simultaneous pressure records in the right auricle and/or the right ventricle and the femoral artery, together with pneumographic tracings, during (a) quiet breathing, (b) deep breathing, (c) prolonged holding of breath in inspiration and expiration with opened or closed glottis and (d) intermittent pressure breathing. In a few cases with artificial pneumothorax, intrapleural pressures were recorded in addition. Examples of simultaneous pressure recording in the right auricle or ventricle, the femoral artery and the pleura in two cases of therapeutic pneumothorax during quiet breathing are shown in Fig. 2.

Interpretation of this and the following records in terms of blood flow variations stems directly from the extension to man, of Starling's law of the heart. If pressures in the right ventricle in successive cardiac cycles are measured exactly at the end of diastole and if the corresponding value of intrapleural pressure is subtracted from it, one obtains the effective diastolic (sometimes called net initial) pressure. This effective diastolic pressure is related to the degree of stretch of the filled ventricle. If the pulse pressure is then measured from the end of diastole to the peak of systole, the degree of response to the stretch and presumably the variations in stroke volume may be qualitatively estimated. An analysis of several hundred cardiac cycles of the tracings obtained in the patient illustrated in Fig. 2 (section B) during quiet and deep breathing has been made in this manner by Dr. Lauson, the result of which indicates a direct linear relationship between the effective diastolic pressure and the pulse pressure of the same beat. In most of our studies the pleural pressure is therefore unknown. However, the pulse pressure variations may be taken as indicating variations in stroke volume in the right heart and as the same argument applies to the left ventricle, variations in pulse pressure in the femoral artery may be interpreted as variations in left ventricular discharge, if in these short intervals the state of the peripheral vascular bed can be considered to be essentially unchanged. Since increase or decrease in peripheral vascular resistance would result respectively in an increase or a decrease in pulse pressure, blood flow remaining the same, this factor must also be taken into account in the interpretation of pulse pressure variation.

Using this method of analyzing tracings it would appear that in normal man during quiet breathing there is no evidence of unequal discharge of both ventricles. This confirms similar observations made by

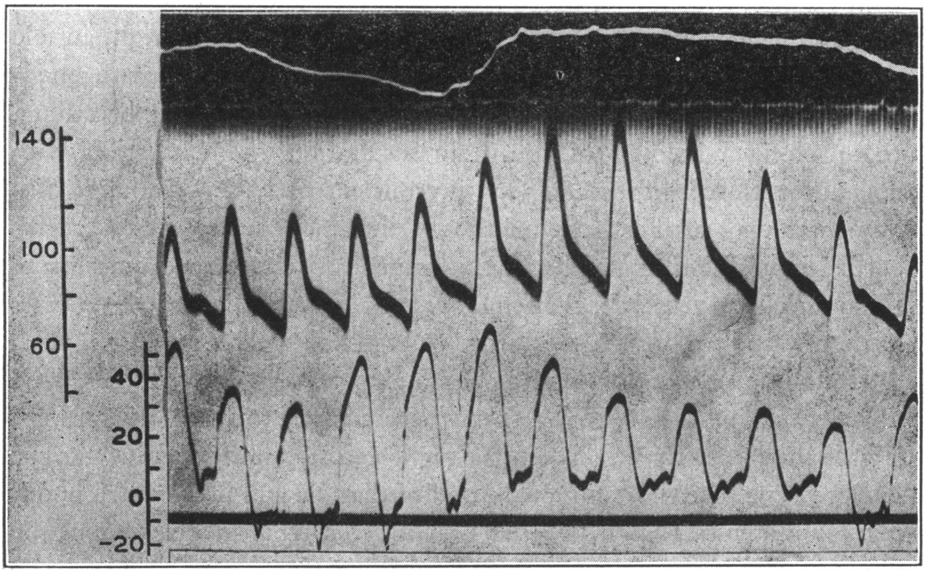

Fig. 3. Simultaneous pneumogram (top row), electrocardiogram (2nd row), blood pressure tracings in the femoral artery (3rd row) and in the right ventricle (bottom row) during deep breathing. Downward stroke of the pneumogram indicates inspiration —upward stroke—expiration.

Hamilton in animals.[15] However, during deep breathing, the evidence is in favor of unequal stroke volume of the two ventricles. In Fig. 3 it is seen that during deep inspiration the pulse pressure in the right ventricle is very large, while it is small in the femoral artery; whereas, the reverse occurs during expiration, when the pulse pressure increases markedly in the femoral artery and decreases in the right ventricle.

The following interpretation may then be given: (a) during inspiration the fall in intrathoracic pressure favors venous return, filling of the auricle and right ventricle. With the consequent rise in ventricular output, the pulmonary arterial mean pressure increases and blood is forced through new capillaries, as the distended lung tends to create an increased resistance in the capillaries already perfused. At the same time less blood is displaced from the actively congested lungs into the pulmonary veins than is being received into the lungs from the pulmonary artery. (b) When the respiratory cycle is reversed, relaxation of the lungs by displacement of blood causes an increase in pulmonary venous return, and left ventricular output, as evinced by a rise in the femoral artery pulse pressure. Meanwhile, the higher intrathoracic pressure

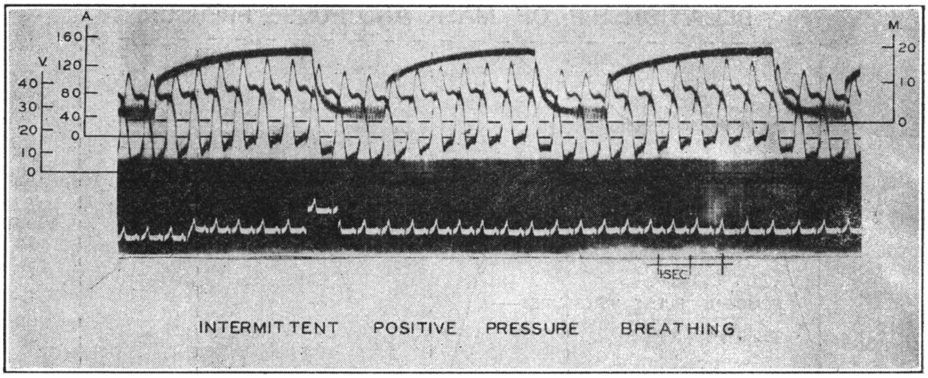

Fig. 4. Simultaneous tracings of mask pressure (M), and blood pressures in the femoral artery (A) and in the right ventricle (V) during intermittent pressure breathing.

decreases the venous return to the right auricle, causing a smaller discharge of the right ventricle.

The mechanism involved in intermittent pressure breathing with positive intrapulmonary pressure inflating the lung, followed by passive deflation, is exactly the reverse of the one just discussed in deep breathing. One typical example of intermittent pressure is illustrated in Fig. 4. The tracings were obtained in a normal young intern who volunteered for the study of a new type of artificial respiration apparatus. Inflation of the lungs under positive pressure and passive deflation were obtained through a special valve converting continuous positive pressure, supplied by a pressure tank, into an intermittent pressure transmitted through a mask to the lungs. It is easy to see the effect of the intrathoracic pressure increase and decrease upon the level of the pressure curves in the right ventricle and femoral artery. But only a beat to beat analysis of pulse pressure changes, in relation to the mask pressures, gives an idea of the magnitude of the probable unequal discharge of both ventricles. This relationship is illustrated in Fig. 5. It is seen that while pressure rises in the mask, the femoral pulse pressure becomes larger presumably as blood is forcibly displaced by the high intra-alveolar pressure into the pulmonary veins, thus increasing the left ventricular discharge. Meanwhile, the pulse pressure decreases in the right ventricle in spite of a marked increase in pulmonary vascular resistance; this points to a smaller discharge from the right ventricle, as the rising intrathoracic pressure causes a reduction of blood return from

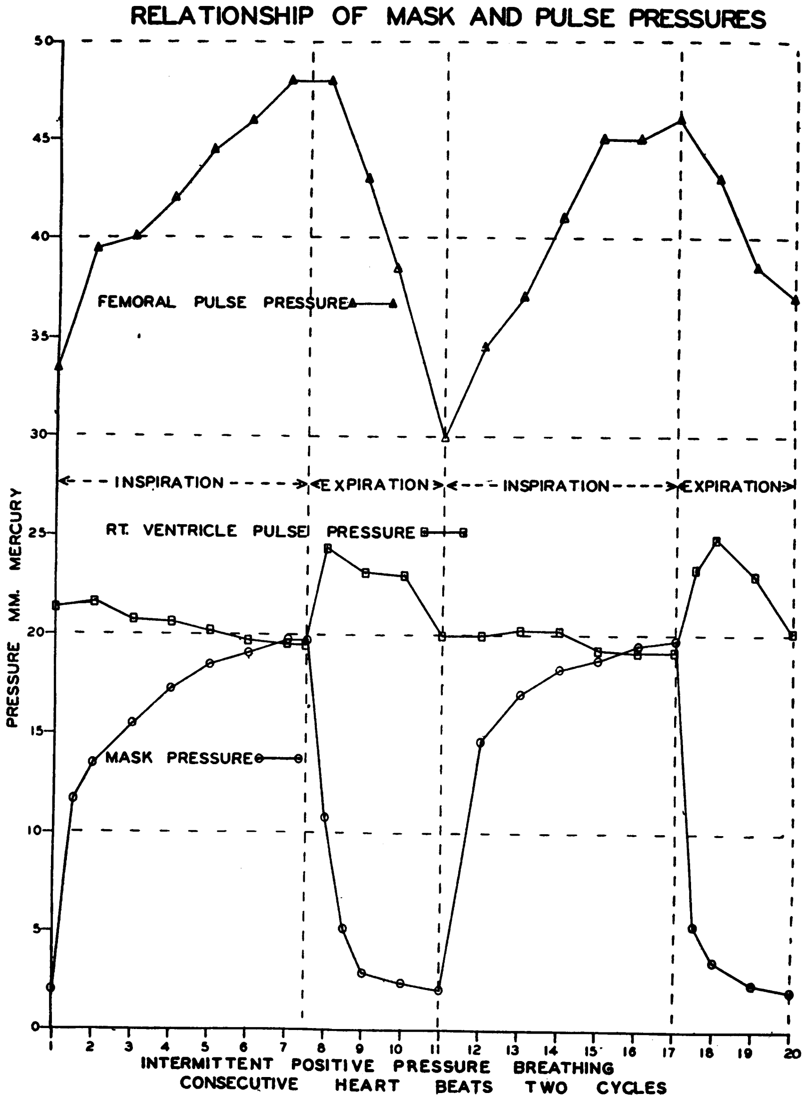

Fig. 5. Chart showing a beat to beat analysis of mask and pulse pressure changes illustrated in Fig. 4.

the large veins into the right auricle. During the short passive expiration the mask pressure falls rapidly, the lower intrathoracic pressure now favors venous return, hence, increased discharge of the right heart reflected in the marked pulse pressure rise. An increasing volume of blood is now held in the lung capillaries the capacity of which suddenly increases as the pressure in the alveoli drops. Therefore, the venous

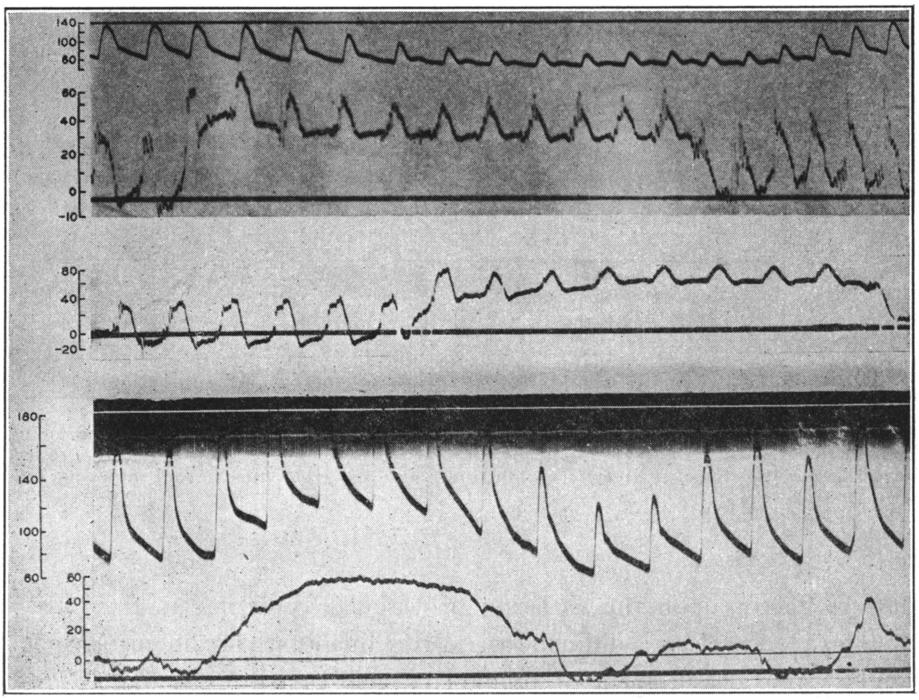

Fig. 6. Effects of a forced expiration upon blood pressure in (a) the right auricle and femoral artery (bottom row), (b) the right ventricle (middle row) and (c) the right ventricle and femoral artery (top row).

return to and the output of the left ventricle is lessened significantly as witnessed by the considerable reduction in the femoral artery pulse pressure.

The modus operandi of intrathoracic pressure variations upon flow, pressures and circulating volumes in the pulmonary circulation becomes clear from these studies: (a) changes in the general level of the pressure curves in the auricle, ventricle, pulmonary artery and veins, and even in the systemic large arteries are passive due to simple propagation of the intrathoracic pressure; (b) variations of the latter influence the venous return and, therefore, the discharge of the right ventricle; (c) finally, the state of distention or relaxation of the lung parenchyma in deep breathing and, in the case of intermittent pressure breathing, the variations of resistance to flow created by intra-alveolar pressure regulate the amount of blood stored, the size of the capillary bed perfused, and the return of blood to the large pulmonary veins. The effects of this pul-

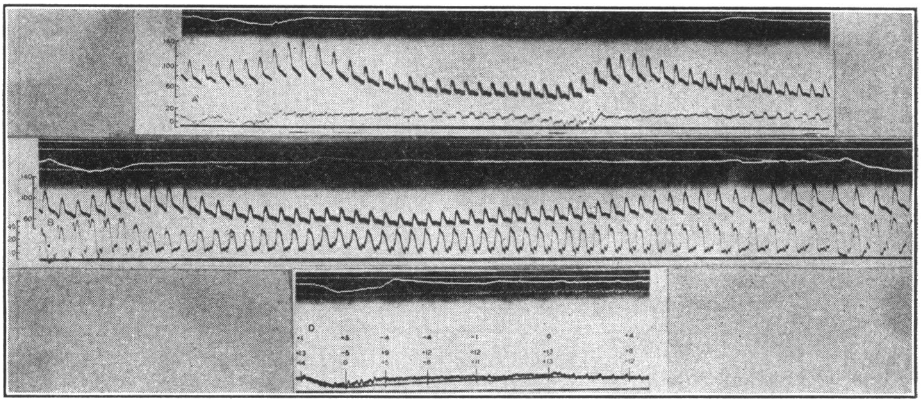

Fig. 7. Effects of a forced expiration maintained over a long interval of time upon the blood pressures in the right auricle and the femoral artery (top row), the right ventricle and the femoral artery (middle row) and the right auricle and a peripheral vein (bottom row).

monary factor upon the variation of vascular resistance in the intra-pulmonary vessels are difficult to express quantitatively in man, since we lack the measurement of pulmonary vein pressure essential to determine the pressure gradient forcing blood through the vascular bed. Animal experiments carried out by Hamilton, Woodbury and Vogt[3] indicate, however, that intra-alveolar pressure variations are effective in temporarily creating marked variation in vascular resistance.

With this background I shall now present briefly the effects of a forced expiration upon right heart and femoral pressures. At the bottom of Fig. 6 are shown tracings of pressures in the right auricle and femoral artery, recorded during a forced expiration of short duration against a closed glottis. The intrathoracic pressure increased markedly as revealed by the auricular tracing and the diastolic pressure level of the femoral artery, but at the same time the femoral pulse pressure became larger indicating greater discharge of the left ventricle. In the next two rows, the effects of the same type of breathing upon the right ventricle discharge are well illustrated by the sharp drop in right ventricular pressure during forced expiration and its rapid rise as inspiration is resumed. The femoral tracing of the first row in addition shows a marked reduction in the diastolic pressure level, associated with a considerable reduction in pulse pressure, indicating that the persistent decrease in output of the right ventricle is followed rapidly by a reduction in discharge of the left.

Some questions regarding the adaptation of the entire circulatory system to such an extreme type of breathing, maintained over a relatively long interval of time are partly answered in Fig. 7. In the top row of this figure, we observe the effects of a prolonged expiration, similar to those just described. In the second row, a ventricular pressure tracing was substituted for the auricular. At first, while the forced expiration progresses, the right as well as the left, ventricular discharge is reduced; this is reflected by the diminishing pulse pressures. After 20 to 24 beats, the pulse pressure rises again, first in the right ventricle, and then in the femoral artery. The mechanism of this secondary rise in right ventricular output is tentatively illustrated in the last row. Simultaneous tracings of pressures in a peripheral vein and in the right auricle were here recorded during the course of a similarly prolonged forced expiration. The figures for pressure in the peripheral vein, and in the auricle, and for the pressure gradient between both indicate that during the Valsalva experiment the pressure in the auricle is higher than in the peripheral vein for a period of time of approximately 13 seconds in this instance; then as blood accumulates in the vein, its pressure progressively rises and presumably the consequent increase in filling pressure initiates the larger discharge of the right ventricle mentioned previously.

Role of the pulmonary vaso-motor system in the regulation of flow and pressures. In our discussion, so far, the active role played by the blood flow and the passive one played by the vascular bed have been emphasized. The question comes up now whether the vaso-motor system plays a part in the regulation of peripheral vascular resistance of the lung vessels. Since anatomists[16] have demonstrated that there exists a dual nerve supply, sympathetic and parasympathetic, going to the muscular structures of the pulmonary vessels, it is in order to find out about its physiologic significance.

To the debate started in the last century and so thoroughly reviewed by Tigerstedt[17] and Wiggers,[18] Hamilton[15] has recently brought new evidence denying that any active role is played by the vaso-motor system in the regulation of blood flow through the lungs in dogs. To a critical analysis of the probable inadequacies of the methods previously used by the proponents of an active vaso-motor system, in particular Daly, [19, 20] he has added experimental evidence acquired with his new method of pressure recording[8] wherein the pulmonary arterio-venous pressure gradient is measured directly in the unanesthetized intact animal. An analysis of the results of his experiment with drugs such as epinephrine, acetylcholine, amylnitrite, and histamine, led him to the following conclusion:[15] (a) that the changes in arterio-venous pressure gradients, when they were present could always be related to changes in blood flow and, therefore, were not necessarily associated with changes in resistance, (b) that the lack of direct effect of the drugs as they were first passed through the pulmonary arterioles was in striking contrast to their immediate action on the systemic arterioles. Extending his argument to the physiologic action of exercise, Hamilton compared the latter effects upon the dynamics of the pulmonary circulation to the effects of the systemic vaso-dilator drugs. According to his views, which confirm previous experimental data obtained by Dunn,[21] as soon as the vaso-dilatation of arterioles rapidly following the onset of exercise, has taken place, venous return and, therefore, pulmonary blood flow increases. However, the pressure in the pulmonary artery and the pressure gradient between pulmonary artery and vein rise very little: the resulting lower quotient of arterio-venous pressure gradient over blood flow then expresses a reduction in pulmonary vascular resistance created by the opening up of many new vascular channels and favoring a more rapid circulation time. A confirmation in man of this purposeful adaptation of the pulmonary circulation to a physiologically induced increase flow, lies in the figures given by Roughton,[6] in the work previously mentioned, of the much shorter capillary time, during heavy work than during rest.

However, to discuss, whether the vaso-motor system plays a significant role in the regulation of the pulmonary circulation in man, we have to resort to indirect evidence, since we lack the essential measurement of arterio-venous pressure gradient. As a first evidence we may use observations which we secured during a study of the treatment of shock in man using the pressor amine methedrine. In Fig. 8 are shown tracings of pressures in the femoral artery and in the right ventricle recorded prior to and at short intervals following the intravenous injection of this drug. In addition cardiac output measurements were made immediately before the first series of tracings and shortly after the last. One notes that the diastolic and the pulse pressure in the right ventricle rose hardly more than by a few millimeters of mercury for

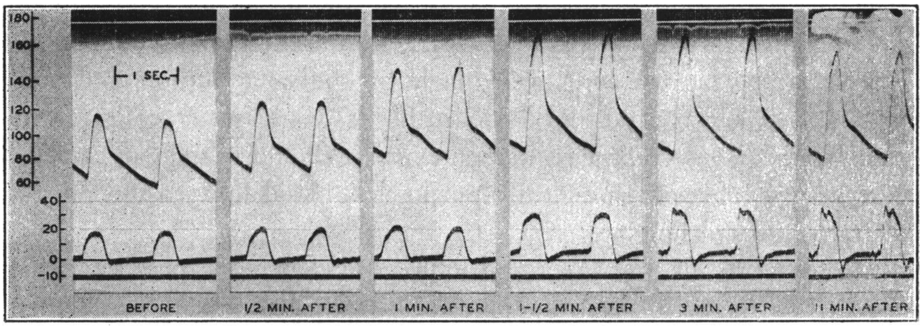

Fig. 8. Effects of the intravenous injection of the pressor amine, methedrine on the blood pressures in the femoral artery (top row) and in the right ventricle (bottom row).

the first 2½ minutes while the pulse pressure and systolic pressure in the femoral artery increased by more than 20 mm. Hg. This would seem to confirm the observations of Hamilton on the absence of direct action of the vaso-constrictive drugs on the pulmonary vessels. The later changes in the right ventricular pressure can probably be explained on the basis of (a) an increased blood flow which, 14 minutes after injection, was approximately 20 per cent larger than the control value, or (b) backflow pressure in the pulmonary vein as a result of increase resistance in the systemic circulation. [2, 22] The second evidence is supplied by some observations, made with Lauson and Bloomfield on right ventricular pressures and cardiac output measurements in 5 cases, with systemic arterial hypertension and good cardiac compensation, who were under the care of Dr. Goldring and Chasis. While the average mean pressure in the systemic circulation was elevated to 128 mm. Hg., the normal being about 95 mm. Hg., the average systolic and pulse pressures in the right ventricle were at the respectively normal figures of 25 mm. Hg. and 23 mm. Hg. Although definite conclusions should await further investigation, it seems reasonable to conclude from these limited data that the biological substance thought to cause increased resistance in the arterioles of the systemic circulation had in these cases no effect upon the arterioles of the lesser circulation. As a third type of evidence we shall have recourse to some observations of change in the arterial oxygen saturation made by Jacobaeus and Bruce,[23] after complete blocking of one main bronchus in normal young volunteers. The marked reduction, which persisted over relatively long periods of blocking, were of the order predicted with half of the mixed venous blood flowing through an unventilated area. Similar observations with nitrogen breathing by one lung were made by the same authors and confirmed since by Wright and Woodruff.[24] It would seem reasonable to think that if a vaso-motor regulation exists, it should in such an extreme case help shunt a physiologically purposeless blood flow to the contralateral ventilated lung.

Considering all this direct and indirect evidence, we may state that the demonstration of vaso-motor effects in the pulmonary circulation of man is still wanting. At best, it may be conceded that if any vasomotor activity exists, under normal physiologic conditions, it is superseded by the much more potent mechanical factors regulating pulmonary blood flow. In contradistinction to the systemic circulation, where variations in peripheral resistance serve to regulate flow to various organs according to their needs, all parts of the pulmonary vascular bed and the alveolar spaces are equal in function, hence, there is little cause for a regulating mechanism of blood distribution under normal conditions.[15]

It remains to be decided whether the vaso-motor system could serve a useful purpose in regulating the amount of blood stored in the lungs. If it is correct, as I have attempted to show, that the variations in pulmonary circulating blood volume are dependent upon (a) the discharge of both ventricles, (b) the state of distension or retraction of the lung parenchyma, and (c) the intra-alveolar pressure, then vaso-motor regulation is not essential. In cases of emergency such as the early period of exercise, the sudden fall of systemic arterial pressure, caused by vasodilatation in the vascular bed of the muscles, may be prevented by an increased discharge of the left ventricle. The conditions favoring this purposeful increase in pulmonary venous return are thought to be (a) either a preliminary passive congestion of the lung, due to a strong epinephrine-like action on the systemic arterioles, with back pressure effects, during the pre-exercise period of excitation,[14] or else (b) a preliminary active congestion of the lungs, due to deep inspirations, the discharge of the left ventricle being then increased by a forceful expiration as exercise starts.[25]

If one agrees with Tiemann and Daiber,[26] that two types of blood channels exist in the lungs, one with active circulation, the other working as a lock, then vaso-motor regulation becomes indispensable. However, against the conception of lung blood depot, as postulated by Hochrein[25] on the basis of this description, there is, it would seem, lack of anatomic justification. As to the clinching physiologic evidence, which lies in the measurements of sequestrated blood, this is, for obvious reasons, still missing.

We shall now turn to the discussion of some observations made during the study of pathological conditions which have an important bearing on the problem of dynamics of the circulation in man.

Clinical investigation of the pulmonary circulation offers an immense field to test physiologic concepts, but methods of study have been until recently inadequate. We shall, here, limit ourselves to the discussion of some problems in which we have been interested:

Mechanism of blood shunting from one part of the lungs to another. Two methods, based on the measurement of respiratory gas exchange may be used in man, to study redistribution of blood, following pneumonia, atelectasis, collapse therapy or partial lung resection, namely (a) the determination in the arterial blood of the oxygen saturation and (b) the simultaneous but separate measurement of each lung's ventilation and gas exchange using the technique of bronchospirometry, which we owe to Jacobaeus, Frenckner and Björkman.[27]

Reduction in arterial oxygen saturation may be taken to indicate that blood circulates in areas of the lungs improperly or not ventilated. In the absence of a simultaneous measurement of the oxygen saturation of mixed venous blood, the degree of arterial oxygen unsaturation, gives only a qualitatively rough approximation of the proportion of blood circulating through unventilated lung areas. In pneumonia and atelectasis, measurements of the arterial oxygen saturation, show that the blood flow persists for some time in unventilated parts of the lungs. Blood is shunted away from these areas only after the pericapillary pressure, due to exudation, transudation and organization of tissue fluids has increased, diverting blood to other channels through better ventilated areas. As we have shown with H. Maier,[28] after lobectomy blood will continue to flow through the poorly ventilated remaining lobe and arterial oxygen saturation may remain low until the latter is again effectively ventilated. In artificial pneumothorax, the arterial oxygen saturation remains normal. According to Hamilton an increased resistance to flow is brought about by the homolateral rise in intrathoracic pressure, and blood flow is redistributed, preferably through the still

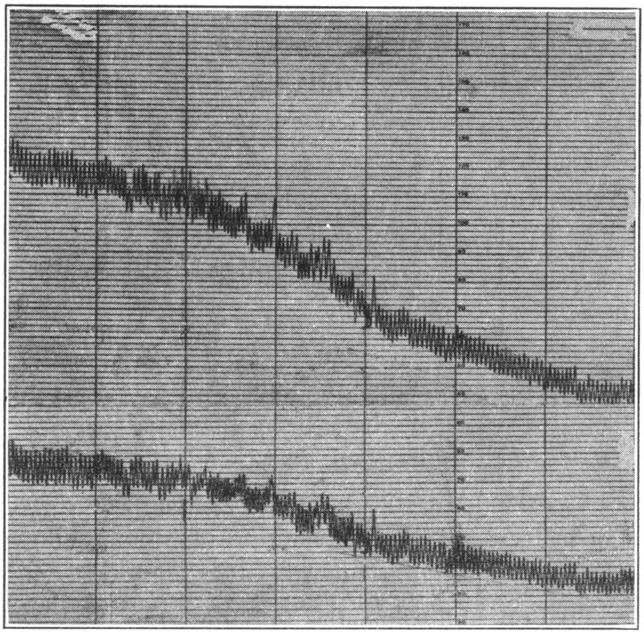

Fig. 9. Simultaneous tracings of ventilation and oxygen intake in each lung separately obtained by the bronchospirometric method. Inspiration upward, expiration downward, oxygen intake of each lung calculated from the slope—vertical lines of the curves at one minute interval—quiet breathing during the first two minutes, leg movements during the next 3 minutes, recovery during the last 2 minutes.

ventilated areas of the collapsed lung and the contralateral lung.

The bronchospirometric method permits a better qualitative estimate of this process of blood redistribution than the measurements of arterial oxygen saturation. The proportional share of each lung in the total oxygen consumption calculated from the slopes of the tracings (Fig. 9) may be taken as a measure of the relative blood flow through each lung, providing the breathing mixture is high in oxygen and the arterial oxygen saturation remains complete. If, in addition, the degree of saturation of the mixed venous blood were estimated directly or indirectly then the absolute values of separate flow could be calculated. In Table II, data on one case with artificial pneumothorax, and one case after lobectomy are presented to illustrate the method. It is seen that in these two patients at rest and during exercise the ventilation and the circulation on the right side were approximately reduced to the same extent.

Very extensive studies having now been carried out in all types of

TABLE II

VENTILATION AND CIRCULATION THROUGH THE RIGHT LUNG AT REST AND DURING EXERCISE IN (a) ONE CASE OF RIGHT ARTIFICIAL PNEUMOTHORAX AND (b) ONE CASE OF RIGHT LOWER LOBE LOBECTOMY

	Rest Normal	Rest Obsv.	Mild Exercise Obsv.
(a) Art. Pnx.			
Right Lung			
Ventilation % of total	55	45	45
Circulation % of total	55	41	45
(b) Lobectomy			
Right Lung			
Ventilation % of total	55	44	39
Circulation % of total	55	40	35

surgical disease of the lungs, of therapeutic collapse and pulmonary resection, the following conclusions concerning the problem of blood shunting are tentatively offered in support of the opinion of Hamilton stated above.

Redistribution of blood flow after partial lung collapse and resection depends upon local mechanical conditions. Among these stand out local ventilation, intrathoracic pressures, and local increase in peri-vascular tissue resistance by parenchymatous organization or by complications such as pleurisy and empyema. A small increase in resistance, in one lung, one lobe, or in lobules will cause the blood to be shunted away from the diseased into the intact lung.

Dynamic adaptation to the reduction or the absence of blood flow through one lung. Since it is assumed that the capacity of the pulmonary vascular bed is great, it would appear that its reduction by half and the routing of the entire blood flow through one lung should have little effect upon vascular resistance and, therefore, right intraventricular pressure.

In Table III are tabulated data in 14 subjects with little or no circulation through one lung which indicate that doubling the blood flow through one lung does not increase the intraventricular systolic pres-

TABLE III

RIGHT VENTRICULAR PRESSURES AND BLOOD FLOW IN 3 GROUPS OF PATIENTS (a) AFTER PNEUMONECTOMY (b) WITH FIBROTHORAX (c) WITH THERAPEUTIC PNEUMOTHORAX

Group	*No. of Cases*	*Right Ventricular Pressures*	*Blood Flow* lit/min/m² BS
		Syst/Diast mm Hg	
(a) Post-Pneumonectomy	5	30/1	3.3
(b) Fibrothorax	4	27/—1	3.4
(c) Artificial Pneumothorax	5	24/0	4.6

sure. In 5 cases of pneumonectomy, three adults and two children, the average right ventricular pressure measured from 4 to 6 years after the lungs were resected, is, in all but one, at the upper limit of normal. In only one case, that of a man of 69 operated on six years previously for a carcinoma of the bronchus and who had then already a significant degree of bilateral emphysema, was there any evidence of pulmonary hypertension, the right ventricular systolic pressure being 36 mm. Hg. In the 4 other cases, the figures are well within the normal range.

In two children of this group studied with Lester and Riley,[29] we measured the maximum oxygen consumption during an exhausting type of exercise and compared them with similar figures in a control group of normal children of the same size and age. In the children with only one lung, the value of maximum oxygen intake, which is related to maximum cardiac output, was identical to the control value. These observations are offered as a further evidence that in subjects with one lung, who were not restrained in their physical activity since pneumonectomy, maximum pulmonary blood flow was not reduced and pulmonary hypertension did not develop after several years. In the four cases of fibrothorax and five of artificial pneumothorax, there was no evidence either of pulmonary vascular hypertension. In one of the cases of fibrothorax, restudied two years later, however, a moderate pulmonary hypertension had developed. The figures are specially significant in the group with artificial pneumothorax, where as a result of the multiplicity of measurement, the figures indicate that the subjects were not nearly under basal conditions as shown by the increased blood flow. In spite of this increased blood flow, the ventricular systolic and pulse pressure remained within normal range.

Preservation of normal pressure-flow relationship in patients with only one normally functioning lung may be achieved in two ways which complement each other: (a) an increase in the number of capillaries which are perfused in the remaining lung, (b) an increase in the diameter of the lung capillaries which according to Poiseuille's law could be very small.

Effect of direct communication between the systemic and the lesser circulation. There is another type of pathological condition where a consistent increase in blood flow through the pulmonary circulation may not be associated with pulmonary hypertension, namely the direct shunt of blood from the aorta to the pulmonary artery through a patent ductus arteriosus.

The technique of right heart catheterization lends itself to a physiologic, rational diagnosis of some forms of congenital heart disease. By the use of pressure recordings in and blood sampling from both branches of the pulmonary artery, the right ventricle, and auricle, congenital defects may be recognized in terms of volume of blood shunted and the effects of the abnormal communication upon pressures may be evaluated. Drs. Dexter and Burwell who have made brilliant use of the resources of the technique of catheterization have already studied six cases of patent ductus arteriosus with surgical confirmation and reported to me recently that in all these cases the pulmonary arterial mean pressure was normal, even though in one individual they estimated the shunt through the ductus to be 8 liters per minute.

We have, however, very recently studied in collaboration with Dr. Janet Baldwin, a young girl of three years of age, with a flow of approximately 5 liters through a patent ductus arteriosus, compared to a systemic flow of 2 liters. A marked degree of hypertension in the pulmonary artery had already developed, the pulmonary artery systolic and diastolic pressures being 55/39 with a mean pressure of 46 mm. Hg. or approximately 3 times normal.

There is no doubt that extension of studies of this type will prove of great value not only in the diagnosis but in the comprehension of the physio-pathology of congenital heart defects.

Influence of chronic pulmonary disease upon the development of

TABLE IV

RIGHT VENTRICULAR PRESSURES, PULMONARY BLOOD FLOW AND LUNG VOLUME MEASUREMENTS IN 17 CASES OF CHRONIC PULMONARY EMPHYSEMA AND FIBROSIS WITHOUT CARDIAC ENLARGEMENT

Group	*No. of Cases*	*Right Ventric. Pressures*	*Blood Flow* lit/min/	*Hct.* %	*Residual Air / Total Lung Vol.* *Pred.*	*Obsv.*
		Syst/Diast mm Hg	m^2 BS		lit.	lit.
A. Emphysema without pulmonary hypertension....	4	24/1	3.0	41	1.3 / 5.3	2.9 / 5.9
B. Emphysema with pulmonary hypertension	4	44/4	3.1	47	1.2 / 5.0	3.6 / 5.6
C. Diffuse fibrosis	9	45/3	3.6	48	1.4 / 5.5	2.2 / 4.2

pulmonary hypertension. The presentation of this problem alone would justify a long discussion. Our concern here is to indicate that an investigative method is available which may help (a) to express somewhat quantitatively the degree of right ventricular strain in chronic pulmonary emphysema and/or fibrosis at a time when radiologic and electrocardiographic data are still equivocal or of no clinical value, (b) to identify the various factors which in these diseases may favor the development of pulmonary hypertension.

In Table IV we have summarized some studies made in collaboration with Drs. Bloomfield, Lauson, Breed and Richards.[4] We have correlated right ventricular pressure, pulmonary blood flow, hematocrit and lung volume measurements in 17 cases without clinical evidence of cardiac enlargement. The first and second groups comprise cases of chronic pulmonary emphysema without and with pulmonary hypertension, the third, cases of chronic pulmonary fibrosis complicated with emphysema. The data are remarkable in showing (a) that pulmonary hypertension had not developed in cases with moderate degree of emphysema, (b) but that in the group with the most marked degree of emphysema, hypertension in the lesser circulation was present, and finally, (c) that in the group with fibrosis and moderate emphysema and apparently small heart, pulmonary hypertension was already quite marked. For a time, it was our impression that polycythemia played a decisive role in the early development of pulmonary hypertension, by increasing the resistance to flow. However, a breaking down of the hematocrit figures in the two groups of emphysema with and without hypertension, does not at present seem to lend support to this hypothesis.

Many factors are responsible for the increased resistance to flow in pulmonary emphysema and fibrosis. With adequate physiologic methods it should be possible to correlate some of the data as we have attempted in this limited series. In the future it will be of interest to the clinician that figures of pressures in the right ventricle and pulmonary artery be correlated with signs usually interpreted as indicating pulmonary hypertension and with studies of electrocardiograms, using the most recent methods for the detection of early right ventricular strain.

In this presentation, I have omitted discussing many problems of interest to the clinician. However, I shall have fulfilled my purpose if I provided adequate support to the following conclusions:

(1) The volume of blood contained in the pulmonary vessels is governed by the relative discharge of the two sides of the heart which are under the control of the dynamic changes in the systemic circulation.

(2) The capacity and the flexibility of the small vessels in the lungs are such that a several fold increase in blood flow may be accommodated with negligible pressure changes, a remarkable example of purposeful adaptation to function.

(3) Under variable physiologic conditions a clear cut demonstration of vaso-motor activity in the pulmonary vascular bed is still lacking.

(4) Sound physiologic methods for the study of the pulmonary circulation are now at the disposal of the clinical investigator and may be used for diagnostic purposes in well chosen cases of congenital cardiac malformation.

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